Maintaining Realistic Uncertainty in Model and Forecast

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LONG-TERM GOALS

Our long term goal is to better understand ensemble forecasting in general and the dynamics of initial uncertainty given only imperfect models in particular; we are most interested in the practical application to a real physical system, rather than toy examples where the model error is known *a priori*. Of particular interest to us are methods which aim to evaluate predictions of high dimensional systems like the atmosphere, methods to best combine different models, and determination of aims which are both achievable by the forecaster and useful for the user.

OBJECTIVES

We wish to establish exactly how it is that uncertainty in the initial condition and imperfections in the model limit the prediction of nonlinear dynamical systems (NDS) like the atmosphere and ocean. Of particular interest is the evaluation and interpretation of ensemble forecasts, now routinely made at the European Centre for Medium-Range Weather Forecasting (ECMWF) and the National Center for Environmental Prediction (NCEP). Particular questions include (i) how to best distribute computational resources between using larger ensembles versus higher resolution models, (ii) when to select a best model versus when to use an ensemble over models, (iii) how to evaluate current ensemble formation schemes and (iv) whether the answers to these questions change when regional forecasts are of interest. While the focus is on geophysical fluid dynamics, the insights gained are applicable across a wide range of forecasting and control systems, including mechanical and industrial processes, and general questions of data analysis and assimilation.

APPROACH

Our initial approach is to develop tests of internal consistency and then apply them in the context of simple numerical and laboratory systems where more reliable statistics can be gathered than in the operational systems. These initial applications often suggest improvements in the technique and understanding which ease application to operational models, where my group's approach has already uncovered several fundamental inconsistencies, both in model formulation and evaluation.
The members of the Pembroke group funded by ONR are:

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14. ABSTRACT

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Leonard Smith (Senior Research Fellow, Pembroke College, Oxford; Reader, London School of Economics)

Mark Roulston (Junior Research Fellow, Pembroke College, Oxford) is investigating methods for generating probabilistic forecasts using multiple ensembles. He is also studying system-model pairs for examining imperfect model issues and the general questions of the selection of model structure. An example of the latter is the choice between linear and nonlinear modeling strategies, as exemplified by his work on modeling the dynamics of El Nino-Southern Oscillation.

Alexandra Guerrero (D.Phil student) has just joined the group and is investigating the use of ensembles consisting of multiple models. Her background is in statistics and she is exploring the data based analysis and identification of stochastic systems including issues of model selection in a nonlinear stochastic framework.

WORK COMPLETED

A general overview of ensemble forecasting and the limitation of

Current ensemble formation schemes, focusing on the perfect model scenario, was completed (Smith, Ziehmann and Fraedrich 1999). Among the conclusions presented were that none of the popular analytic methods of estimating predictability based upon linearization of the system equations (Lyapunov exponents, doubling times, *etc*.) gave real insight into local predictability: fully nonlinear ensemble forecasts are required.

Tests we developed were used to evaluate the duration of the linear regime in operational weather forecasts, this is a crucial parameter in determining the consistency of ensemble formation techniques based on singular vectors; this work is now in review (Gilmour, Smith and Buizza 2000). It indicates that the duration of the linear regime in operational weather forecasting models is much shorter than commonly assumed, implying that some operational ensemble formation schemes are not internally consistent (Gilmour 1999).

A new variety of shadowing trajectory was defined (see Smith 2000a), and used to show the limitations model error puts on data assimilation techniques. In particular, the general conclusions of Lorenz and Emmanuel (1988) on the relative merits of different schemes for making adaptive observations (selecting which additional observations to make among a wide range of potential observations), were significantly modified, and extended to the imperfect model case. Methods to test the relevance of our conclusions in an operational setting were developed (Hansen and Smith 2000).

A new cost function was derived showing the limitations of the common one step least squared error criterion; at present applications are limited to low dimensional systems, but both deterministic and stochastic models are considered (McSharry and Smith 1999).

Review of the goals of ensemble forecasting in the face of real world limitations was begun, and alternative (achievable) targets were identified to replace ideal (but unphysical) targets. The existence of an infinite number of 'indistinguishable states' has been proven, even give a perfect model and observations extending back arbitrarily far into the past. This makes the formation of a perfect ensemble unattainable even given a perfect model and calls the possibility of making accurate forecasts of probability density functions (PDFs) into question (Smith 2000a, Judd and Smith 2000).

Quantification of the relative benefits of ensemble size versus model accuracy have been derived in the special case of Gaussian uncertainties; the smallest ensemble size likely to capture "truth" within the bounding box of the ensemble (an alternative to aiming for an accurate PDF), has been computed as a function of the model bias and the standard deviation of the perturbations used to form the ensemble.

Using models suggested by Lorenz (1996), a scheme has been developed to provide a test bed for exploring the improvement of parameterization of sub-gridscale processes and the understanding of model sensitivity to parameters.

Minimal Spanning Trees (MST) have been used to generalize the Talagrand diagram to higher dimensions, thereby allowing more robust assessment of ensemble forecasts (Smith 2000a).

RESULTS

A skill score, specifically designed for probabilistic forecasts has been proposed by Roulston and is now being investigated. It has now been shown that this skill score is a more relevant measure of forecast skill than previous skill scores (e.g. Brier Score) in cases where the users of the forecast must essentially "gamble" on the weather.

A rational method for combining ensemble forecasts with knowledge of climatology has been developed. It has been found that this method leads to a reduction in the variability of the skill of probabilistic forecasts in the context of perfect ensembles. The utility of this method will be tested using ECMWF ensemble forecasts.

IMPACT/APPLICATIONS

Current results indicate that even in paradigm chaotic systems like nonlinear electric circuits, chaos provides less of a barrier to prediction than model error (Smith 2000a,2000b). We believe that this may be true for most physical; in particular we have found that persistent, state dependent, error exists in the ECMWF operational model (Orrell *et al.* 2000). This work is the focus of the doctoral thesis of Mr. David Orrell, a D.Phil student in our group funded by ECMWF and the British government. A large impact should be expected wherever this is found to be the case, as it suggests a redistribution of resources between model development, data assimilation and ensemble forecasts.

The development of standard system-model pairs in which the model is an imperfect representation of the system. Such pairs should enable results valid in the perfect model context to be generalized to imperfect models.

Further work on generating probabilistic forecasts using multiple ensembles and multiple models should lead to greater user value for operational weather forecasts. In particular, we are translating ensemble weather forecasts into ensemble forecasts of quantities of direct interest to the user (e.g. the distribution of likely electricity demand or the distribution of the likely landing rate (planes per minute) on a given runway.)

We have clarified a technical confusion in the atmospheric science literature: two distinct types of localized Lyapunov exponents with rather different properties were both being called "local Lyapunov exponents" leading to incorrect conclusions. These have been clarified (Smith, Ziehmann and Kurths 2000).

TRANSITIONS

Prof. David Kenning (Engineering Dept., Oxford) is using the modeling techniques we have developed to study the dynamics of boiling and heat transfer. Dr. Jost von Hardenberg has joined our group to study spatial-temporal patterns in boiling, and brings expertise both in that field and in geophysical fluid dynamics in general.

RELATED PROJECTS

1- Vortex system-model pair. A system-model pair is being developed by Mr. Edgar Perez, a D.Phil student funded by the government of Mexico. The system consists of a collection of n point vortices which is completely defined by 2n first order ordinary differential equations. The flow field associated with this system is modeled using a finite element or spectral code. This system-model pair will be used to investigate issues that arise when model are imperfect, in particular that even a low order system may require a high resolution model.

2- Numerical simulation of physical systems and the role of error in the model-class. Mr. Reason Machete has completed a MSc project working with both Smith and Roulston: the project contrasts the integration of the Moore-Spiegel system using numerical methods versus the output of a custom built analogue electrical circuit. It is hoped that this can provide another system-model pair for investigating imperfect model issues.

3- The search for response manifolds in the parameter space of climate models. Barbara Casati has completed an Msc project (under the supervision of Smith) which investigated a method for determining whether the response of a model to parameter changes can be explained using a reduced set of parameters. No evidence for the existence of such manifolds was found.

4- Information theoretic based decompositions. British Energy (formerly Nuclear Electric) has funded a D.Phil studentship which Mr. Liam Clarke has taken up under my supervision. The aims of this project include developing nonlinear extenstions of Proper Orthogonal Decomposition (POD) and methods of model formation when many multiple inputs are available.

5- NCAR climate model output analysis. 100,000 days of perpetual January from NCAR's atmospheric model is being analyzed using methods devised for studying nonlinear systems; in particular to determine the time scales for useful analogies and as an example of how to make the choice between linear models or nonlinear models and how it varies as the duration of observations increases.

6- The value of ensemble weather forecasts. The value of ECMWF ensemble forecasts to decision makers is being determined in a project funded by ECMWF. The aim is to establish the conditions under which a probabilistic ensemble forecast has value above a traditional deterministic forecast. The value obtained versus the size of the ensemble will also be found.

7- Casino-21. Our group is active in the formulation of an ensemble climate modeling project which aims to use privately owned personal computers in a massive parallel computing scheme. One of us (Smith) is on the Casino-21 steering committee, while both Smith and Roulston are involved in issues of experimental design.

8- Linear and nonlinear models of El Nino-Southern Oscillation (ENSO). Roulston is leading a study to contrast nonlinear models of ENSO (forecasts on time scales from 3 months to over a year). A general methodology is applied and the relative quality of global linear models (given the current duration of the data) are established.

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